On the dynamics of the dayside low latitude F-region ionosphere:Formation of the equatorial anomaly and stratification of the F2 layer

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論 文 内 容 要 旨

In this thesis, analyses of the bottom side sounder data obtained from SEALION and the topside sounder data obtained from the OHZORA (EXOS-C) and ISIS-2 satellites, and the model calculations using the SAMI2 code were performed in order to clarify the features and mechanism of stratification of the F2 layer.

Recent sophisticated observations and model calculations have revealed that the ionosphere still contains unsolved problems, in particular, problems related to the coupling process between the ionosphere and the

thermosphere, although the basic structure and dynamics of the ionosphere have been believed to be well understood to date. We focused on stratification of the F2 layer which is strongly concerned with the interaction between the ionospheric plasma and the thermospheric neutral gases. Studies on stratification of the F2 layer have a long history, and this stratification has been individually observed from the ground and from the topside ionosphere as the F3 layer and the ionization ledge, respectively. However, the relationship between the two has not been clarified, and some unexplained problems still remain for each phenomenon. In order to clarify the structure and dynamics of the F3 layer and the ionization ledge and the relationship between the two, we analyzed the bottom side sounder data obtained from the SEALION and the topside sounder data obtained from OHZORA and ISIS-2 satellites, and performed model calculations using the SAMI2 code.

In order to clarify stratification of the F2 layer viewed from the ground, called the F3 layer, bottom side sounder data obtained from SEALION were analyzed. It was confirmed in a magnetic meridional plane including the both northern and southern hemispheres that the temporal variation and the occurrence probability of the F3 layer depend on the magnetic latitude. The analysis results of ionogram data observed on 04 and 31 March 2005 at Chiang Mai (CMU; geographic latitude 18.8°N, geographic longitude 98.9°E, and magnetic latitude 13.2°N), Chumphon (CPN; 10.7°N, 99.4°E, and 3.2°S) and Kototabang (KTB; 0.2°S, 100.3°E and 10.1°S) are summarized as follows: On 31 March 2005, the F3 layer occurred at all stations. At CPN, located near the magnetic equator, the F3 layer moved rapidly upward, and its duration time was shorter than those at CMU and KTB, the northern and southern magnetic low latitude regions. The behavior of the F3 layer was similar at CMU and KTB. The virtual height was more or less constant and its duration time was longer than that at CPN. When the F3 layer was observed at CMU and KTB, the plasma density at the F3 peak did not decrease but it increased. On 04 March 2005, the F3 layer was only observed at CMU and KTB. As was the case on 31 March 2005, the temporal variation of the F3 layer at CMU was similar to that at KTB. The results of statistical analysis during the period in October in 2004, from February to September in 2005 and from November in 2006 to January in 2007 are summarized as follows: At CMU, the occurrence probabilities became lowest in the December solstice season. At CPN, it became highest in the June solstice season. At KTB, it was high in all seasons. The occurrence probability of the F3 layer at CPN was lower than those at CMU and KTB in all seasons. The occurrence of the F3 layer at CPN was localized in the morning period, while the occurrences at CMU and KTB were extended from the morning to pre-sunset local time. In the December solstice season, the difference of the occurrence probabilities between CMU and KTB was conspicuous.

As a result of the model calculation for the F3 layer, it was confirmed that the SAMI2 model can reproduce the observed features of the F3 layer. It was clarified by the model calculation as well as the data analysis that the field aligned diffusion of plasma plays a positive role in forming the F3 layer. From comparing the calculated location of the F3 peaks and plasma density distribution, it was found that the F3 layer corresponds to the plasma density enhanced region associated with the equatorial anomaly. Since the altitude of the F2 layer existing below the F3 layer and the peak height of the production rate of plasma are comparable, the F2 layer is formed by the photo-chemical and dynamical processes as suggested by Balan et al. (1998). The meridional neutral wind modulates the location of the plasma density enhanced region. The mechanism of the F3 layer was suggested as follows: The F3 layer corresponds to the density enhanced region associated with the equatorial anomaly. This enhanced region moves upward and to a higher latitude region due to the

$\mathbf{E} \times \mathbf{B}$ drift and the field aligned diffusion. When it reaches the altitude sufficiently separated by the F2 layer at a lower altitude, the plasma density enhanced region becomes observable from the ground as the F3 layer. The density enhanced region continues to move to a higher altitude and a higher altitude latitude region, so that the F3 layer is shifted to a latitude region.

On the other hand, in order to clarify the features of stratification of the F2 layer viewed from the topside ionosphere, called the ionization ledge, topside sounder data obtained from the OHZORA and ISIS-2 satellites in the American longitudinal equatorial ionosphere were analyzed. The following results were obtained by analyzing the topside sounder data. The ionization ledge occurred near the dip equator. The peaks of the ionization ledge were roughly aligned along a similar field line (the ledge field line). The ionization ledge was observable during almost all local time periods except for the local time period from 03 LT to 08 LT. The occurrence probability of the ionization ledge was highest at noon. Comparing the eastward electric field deduced from the variation of the horizontal component of the geomagnetic field, the ionization ledge occurred when upward movement of the ionospheric plasma due to the $\mathbf{E} \times \mathbf{B}$ drift became large. This result is a first observational evidence that the $\mathbf{E} \times \mathbf{B}$ drift is the main generation factor of the ionization ledge. The seasonal dependence of the occurrence probability of the ionization ledge became higher in the equinox seasons and lower in the solstice seasons.

As a result of the model calculation for the ionization ledge, it was confirmed that the SAMI2 model can reproduce the observed features of the ionization ledge. It was clarified by the model calculation that the seasonal dependence of the occurrence probability is controlled by not only the $\mathbf{E} \times \mathbf{B}$ drift but also by the meridional neutral wind. From comparing the apex altitude of the ledge field line with the altitude profile of the field aligned total electron content, it was found that the ledge field line corresponds to the density enhanced flux tube, and that the height variation is controlled by the $\mathbf{E} \times \mathbf{B}$ drift. It was confirmed by the model calculation that the ledge field line and the magnetic field line passing through the equatorial anomaly crest are the same during the daytime and are separate from each other during the night time. It was also suggested that this separation is possibly caused by the faster chemical loss of plasma in the equatorial anomaly crest at a higher latitude. It was suggested that the neutral anomaly is not a necessary condition for formation of the ionization ledge. The mechanism of the ionization ledge was suggested as follows: The plasma density enhanced flux tube was generated through the photo-chemical process at the altitude just above the F2 peak over the magnetic equator in the early morning local time. This flux tube rises upward by the $\mathbf{E} \times \mathbf{B}$ drift. When the altitude of this flux tube is sufficiently separated by the F2 layer at a lower altitude, the ionization ledge becomes observable from the topside ionosphere. The ledge field line becomes separated from the magnetic field line passing through the equatorial anomaly crest during the night local time due to the faster loss of plasma in the equatorial anomaly crest at a higher latitude.

One of the most important results is that the dynamics of the F3 layer and the ionization ledge cannot be understood by the one dimensional variation in altitude. The dynamics of these phenomena can be understood in the two dimensional frame of the whole magnetic meridional plane connected by the magnetic field lines. Based on the different tendency of the occurrence probabilities and the different mechanisms of each phenomenon, it is concluded that it is not necessary for the ionization ledge to accompany the F3 layer. The ionization ledge is not a deformed F3 layer due to the chemical loss and the field aligned diffusion processes. Therefore, it is concluded that they are not the same phenomenon.

As mentioned above, the features of stratification of the F2 layer have become understandable, however, it should be noted that the present model calculation can not reproduce the F3 layer on a day-to-day basis. The day-to-day variation of the daytime ionosphere is a problem to be urgently solved not only for stratification of the F2 layer but also for the other phenomena occurring in the low latitude F-region, such as the equatorial spread-F. In order to clarify the day-to-day variation, ground based observations of the daytime $\mathbf{E} \times \mathbf{B}$ drift and meridional neutral wind are required. We proposed a possible application method of the F3 layer to diagnose the daytime meridional neutral wind by performing the model calculation to reproduce the occurrence and temporal variation of the F3 layer observed by the SEALION bottom side sounders at CMU, CPN and KTB. This application has great potential for deriving the daytime meridional neutral wind on a day-to-day basis. It should be noted that this method diagnoses the meridional neutral wind effect on the ionospheric structure which is expressed by the product of the collision frequency and the velocity difference between the ion and the neutral wind. The collision frequency between O and O^+ has variance of a factor of about 2. Therefore, simultaneous and in-situ observations of the thermospheric neutral wind and the ionospheric plasma are required. For this purpose, we carried out insitu plasma density and plasma wave measurements by the PWM system onboard the sounding rocket (S520#23) in the WIND campaign on 02 September 2007. In the campaign, accurate measurements of the neutral wind and physical quantities of plasma were successfully carried out at the same time. A detailed picture of the coupling process between the ionospheric plasma and the thermospheric neutral gases and the collision frequency will be acquired by combining the observational data. These approaches will give new insight into the ionosphere-thermosphere coupling problem.

論文審査の結果の要旨

電離圏研究はその発見以来長い歴史を持ち、その古典的な理解は確立している。しかし近年の観測技術や計算機シミュレーションの飛躍的発展により、新たに浮かび上がってきた諸問題は特に中性大気とプラズマの運動量交換を通じた相互作用の視点から、惑星の持つ大気と宇宙プラズマの相互作用の問題への広がりを見せるに至っている。本論文ではこのような背景から地球の赤道域電離圏において未解決の問題として残されてきたF2層の複層化の問題に焦点を当て、新たな観測手法と計算機シミュレーション法を用いてその解明にあたり、これを基礎とした中性大気とプラズマの相互作用問題としての理解を得ることを目的としている。

赤道域電離圏は赤道異常を代表とする特異な構造を呈するが、赤道異常に伴う電離層F2層の複層化現象として、地上観測からはF3層が、人工衛星観測からはIonization Ledgeと呼ばれる現象が知られている。本論文ではF2層複層化現象の定量的振る舞いを、SEALIONイオノゾンデネットワーク観測、トップサイドサウンダー衛星観測並びにSAMI2計算機シミュレーションモデルを用いて究明し、その全貌を統一的に解明した。

先ずSEALIONネットワークによるイオノゾンデ観測データ解析では、磁気赤道近傍にあるチュンポン（CPN）を挟んで北半球側のチェンマイ（CMU）、南半球側のコトタバン（KTB）の観測点でのデータを使用した結果、F3層発生の問題の解決のためにはプラズマダイナミクスと中性風の季節変化について2次元モデルによる理解が必要である点、従来考えられてきたモデルとは異なり、沿磁力線拡散の寄与はF3層出現を促進させる向きに働く点を見出した。

次に「おおぞら」衛星並びにISIS衛星による観測データの解析を行い、Ionization Ledge出現の季節依存性や電離圏電場との関係などに関して、その実体を初めて詳細に明らかにする事ができた。また計算機シミュレーションを用いての再現を行い、Ledge はプラズマ密度の増加したフラックスチューブとして現れる点、南北向きの中性風が存在した場合には出現が抑制される点などを明らかにした。本論文のまとめとしてF2層の複層化の実体が明らかになった事から、今後の展望として本論文の研究手法を用いることで、スプレッドF、プラズマバブルや電離圏日々変動を解明する方法論が確立し、今後の電離圏擾乱の予報にも繋がる点、また中性風とプラズマ間の運動量輸送のプロセスをこれらの現象を用いて解明してゆくことができる点を示すことができた。

これら本博士論文の主たる成果の多くは既に学術誌掲載論文、国内外の学会・研究会を通じての研究成果の公表実績などを有し、著者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。従って上本純平提出の博士論文は、博士（理学）の学位論文として合格と認める。